

GATE Center of Excellence in Innovative Drivetrains in Electric Automotive Technology Education (*IDEATE*)

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Project ID: TI 021

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Overview

Timeline

- Start: 10/1/2011
- Finish: 9/30/2016
- 50% complete

Barriers

- Lack of advanced technology curricula
- Lack of trained engineers and scientists

Budget

- Project funding:
 - ◆ DOE share: \$954.2 K
 - ◆ Cost share: \$253.4 K
- Government funding received in:
 - ◆ FY13: \$164.3 K
 - ◆ FY14: \$161.0 K
- \$321.2 K spent (34%)
(as of 3/31/2014)

Partners

- University of Colorado Colorado Springs (*project lead*)
- University of Colorado Boulder
- Utah State University
- Industry Advisory Board: *Arbin Instruments, Chrysler, Ford Motor Company, General Motors, Infield Capital, LG Chem Power Inc, Linear Technology, NREL, Nilar, Siemens, Tesla, Texas Instruments*

Relevance/Objectives of *IDEATE*

- Establish a Graduate Certificate in Electric Drivetrain Technology
- Establish an MSEE option in Battery Controls and an MSEE emphasis area in Vehicle Power Electronics to educate a future workforce
- Develop courses and materials that support fundamental research, which will enable development of new technology in IDEATE topics
- Remove barriers to study by making IDEATE coursework nationally accessible via on-line means, and offering GATE Fellowships

Graduate Education in **Battery Controls**

UCCS University of Colorado **Colorado Springs**

Graduate Education in **Vehicle Power Electronics**

CU University of Colorado **Boulder**
Utah State University

Graduate courses supporting PhD in EE emphasis area in *Battery Controls*

- Feedback Control
- Digital Control
- Multivariable Ctrl. Systems I, II, III

MSEE option in *Battery Controls*

- Optimization
- System Identification
- Kalman Filtering
- Model Pred. Ctrl.

Graduate Certificate in *Electric Drivetrain Technology*

- Modeling Battery Dynamics
- Battery Management & Ctrl.
- Power Electronics for Electric Drive Vehicles
- Adjustable Speed AC Drives

MSEE emphasis area in *Vehicle Power Electronics*

- Intro. to Pwr. Elect.
- Res., Soft Switch
- Model/ctrl Pwr. Elect.
- Pwr. Elect Lab

Graduate courses supporting PhD in EE emphasis area *Vehicle Pwr. Elect.*

- Analog IC Design
- Mix. Signal IC Des.
- Renewable Energy
- Ctrl. Sys. Analysis
- Embed. Sys. Des.
- Digital Control Sys.

Relevance of *IDEATE* Objectives

Addresses barrier 1: Lack of advanced technology curricula

- Creation of five new specialty courses:
 - ◆ Modeling, Simulation and Identification of Battery Dynamics
 - ◆ Battery Management and Control
 - ◆ Optimization Methods for Systems and Control
 - ◆ Power Electronics for Electric Drive Vehicles
 - ◆ Adjustable Speed AC Drives

Addresses barrier 2: Lack of trained engineers and scientists

- Graduate certificate in Electric Drivetrain Technology retrain engineers
- MSEE option/emphasis areas educate a future workforce
- Supports fundamental MSEE/PhD research in *IDEATE* topics to continuously advance knowledge in the field
- Removes barriers to study by making *IDEATE* coursework nationally accessible via on-line means, and through offering GATE Fellowships

Key *IDEATE* Milestones During FY14

Planned date	Category	Description	Status
09/2013	Go/No-go	All new courses developed	Passed
09/2013	Go/No-go	Minimum of 30 students apply for and enter IDEATE program	Passed
12/2013	Milestone	Offering of ECE5510 complete	Complete
12/2013	Milestone	Offering of ECE5520 complete	Complete
12/2013	Milestone	Offering of ECEN5797 complete	Complete
12/2013	Milestone	Offering of ECEN5827 complete	Complete
01/2014	Milestone	Advertisement placed	Complete
01/2014	Milestone	Generate newsletter to IAB	Complete
01/2014	Milestone	ECE5510 packaged for on-line delivery	Complete
01/2014	Milestone	ECE5520 packaged for on-line delivery	Delayed*
04/2014	Milestone	Applications for fellowships reviewed	On schedule
05/2014	Milestone	Offering of ECE5530 complete	On schedule
05/2014	Milestone	Offering of ECEN5517 complete	On schedule
05/2014	Milestone	Offering of ECEN5817 complete	On schedule
05/2014	Milestone	HW talking with PC via CAN/COM	On schedule
05/2014	Milestone	HW simulating current using D2A	On schedule
05/2014	Milestone	HW calculating, producing cell voltages	On schedule
06/2014	Milestone	ECE5530 packaged for on-line delivery	On schedule
07/2014	Milestone	First students complete MSEE option	Complete

*Anticipated completion in summer 2014.

Approach: Uniqueness of *IDEATE*

- The University of Colorado Boulder (CU-Boulder) is widely regarded as having one of the top U.S. graduate programs in ***power electronics***
- The University of Colorado Colorado Springs (UCCS) has unrivaled expertise in algorithms for ***automotive battery control***
- By collaborating, IDEATE builds on our team's proven strengths to ***develop innovative curricula*** and to ***initiate courses and programs*** that will provide students with a ***unique opportunity for holistic and specialty education in electric drivetrain technology***
- Graduates from these programs will provide benefit not only to major automotive manufacturers, but also to new electric drivetrain focused small businesses and suppliers



Approach: Principal Overall *IDEATE* Tasks

Administrative (☑ = complete)

- ☑ Undergo university processes to have Graduate Certificate and MSEE option approved
- ☑ Create processes for admissions, graduation
- ☑ Create processes for review of GATE Fellowship applications and funds disbursement
- Advertise availability of programs (ongoing)
- Process applications and GATE Fellowship requests (ongoing)
- Generate newsletters for IAB, soliciting feedback (ongoing)

Curricular

- ☑ Create curriculum and teaching materials for five new courses
- ☑ Implement new laboratory
 - Refine curriculum/teaching materials based on own observations, IAB input (ongoing)
 - Offer certificate and related MSEE courses (ongoing)
 - Package MSEE-BC courses for on-line delivery (started)
 - Develop hardware battery simulator for laboratory (started)

Approach: Principal *IDEATE* Tasks, FY14

Administrative

- Advertise availability of programs
- Process applications and GATE Fellowship requests
- Generate newsletter for Industry Advisory Board, soliciting feedback

Curricular

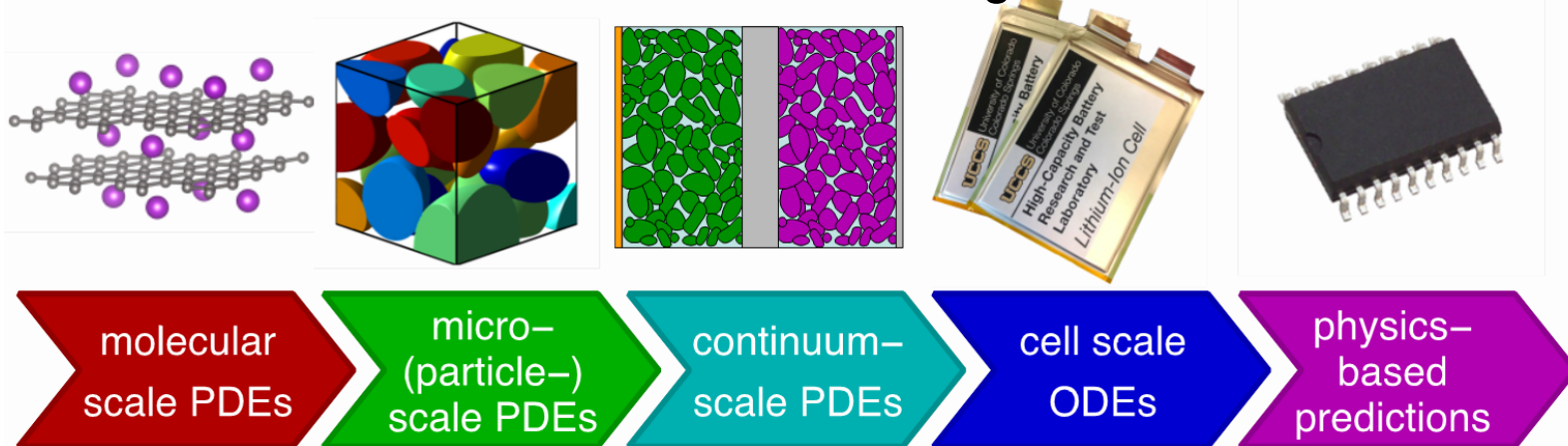
- Refine curriculum/teaching materials for courses
- Offer certificate courses: ECE5710, ECE5720, ECEN5017, ECEN5737
- Offer MSEE-BC courses, ECE5510, ECE5520, ECE5530
- Begin packaging MSEE-BC courses for on-line delivery

Future tasks

- Continue packaging MSEE-BC courses for on-line delivery
- Software development for hardware battery simulator platform
- Refresh courses based on IAB feedback and experience

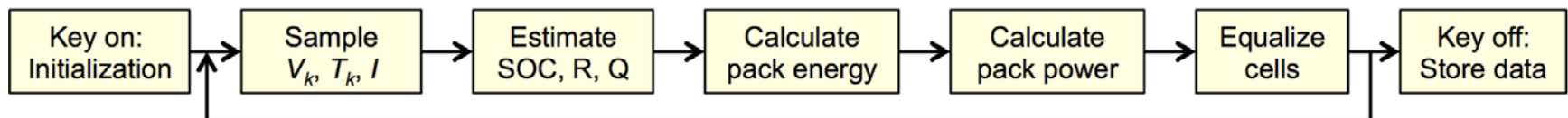
Ongoing Tech. Accomplishment: Curricular

- Refined curriculum and teaching materials for *ECE5710: Modeling, Simulation, and Identification of Battery Dynamics*. Offered Fall 2012/13
 - ◆ Brief consideration of equivalent-circuit models and their limitations
 - ◆ Substantial attention given to deriving meso-scale homogeneous-phase physics-based models of internal cell dynamics
 - ◆ Volume-averaging techniques used to create continuum models via porous-electrode theory
 - ◆ Cutting edge methods for automatically converting continuum models to reduced-order controls models investigated in detail



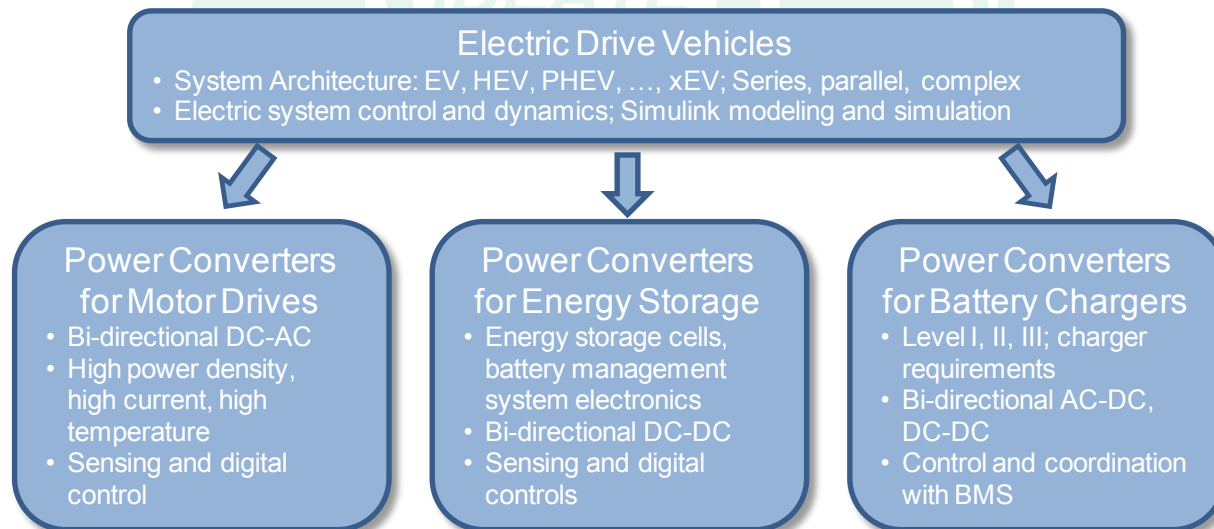
Ongoing Tech. Accomplishment: Curricular

- Refined curriculum and teaching materials for *ECE5720: Battery Management and Control*. Offered Spring 2013, 2014
 - ◆ Overview of the major functions of a battery management system
 - ◆ In-depth consideration of several methods for battery state estimation
 - ◆ Some standard and improved methods for battery health estimation
 - ◆ Motivation and methodology for cell balancing
 - ◆ Voltage-based power limit estimation
 - ◆ Aging mechanisms and degradation models
 - ◆ Optimized controls for power estimation



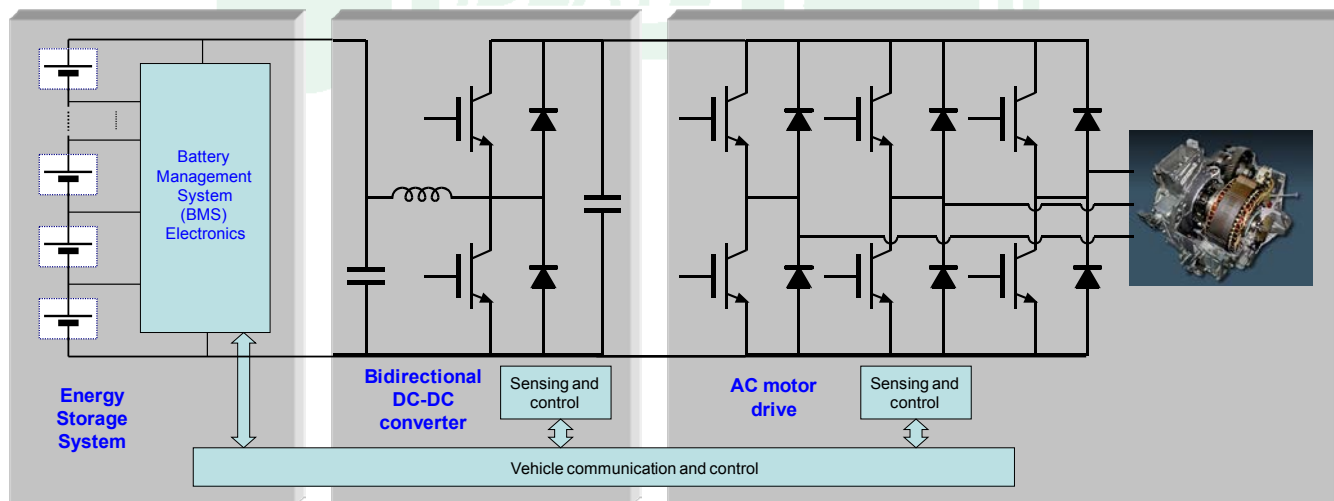
Ongoing Tech. Accomplishment: Curricular

- Refined curriculum and teaching materials for *ECEN5017: Power Electronics for Electric Drive Vehicles*. Offered Fall 2012, 2013
 - ◆ Electric drive vehicle system architecture
 - ◆ Electric system control and dynamic modeling in Simulink
 - ◆ Power converters for motor drives
 - ◆ Power converters for energy storage, battery management electronics
 - ◆ Power converters for battery chargers and utility interface



Ongoing Tech. Accomplishment: Curricular

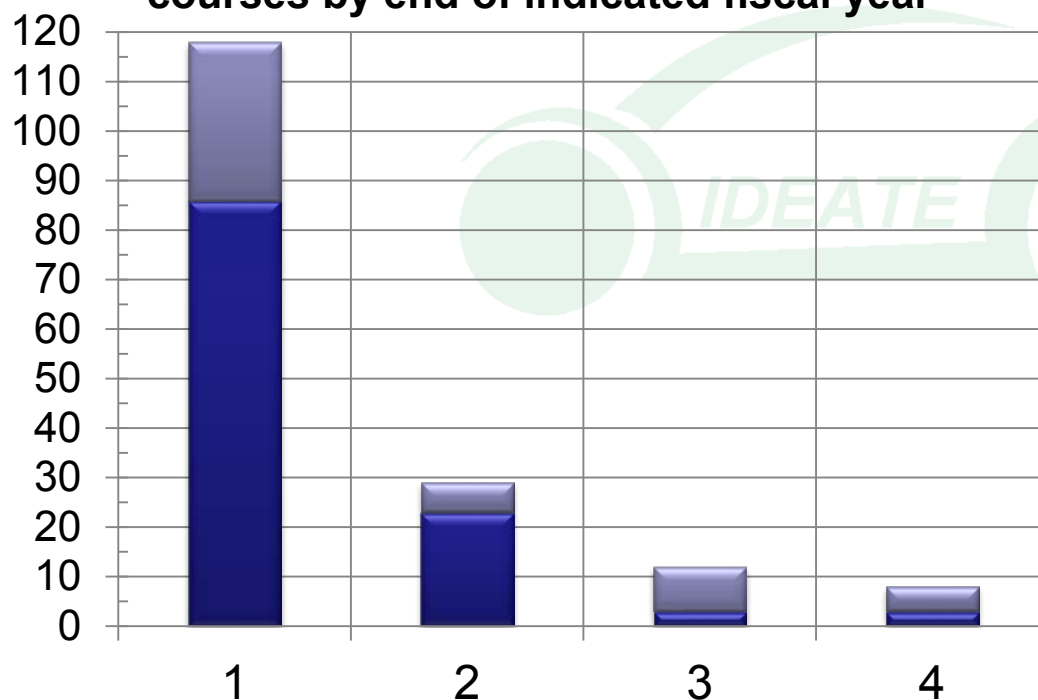
- Refined existing course *ECEN 5737: Adjustable Speed AC Drives* curriculum and teaching materials to be direct companion to the *Power Electronics for Electric Drive Vehicles* course. Offered Spring 2013, 2014
 - ◆ Introduction to electric machines for electric vehicles
 - ◆ Principles for analysis of electric machines, reference frame theory
 - ◆ Operation and control of symmetrical induction machines
 - ◆ Operation and control of permanent-magnet synchronous machines



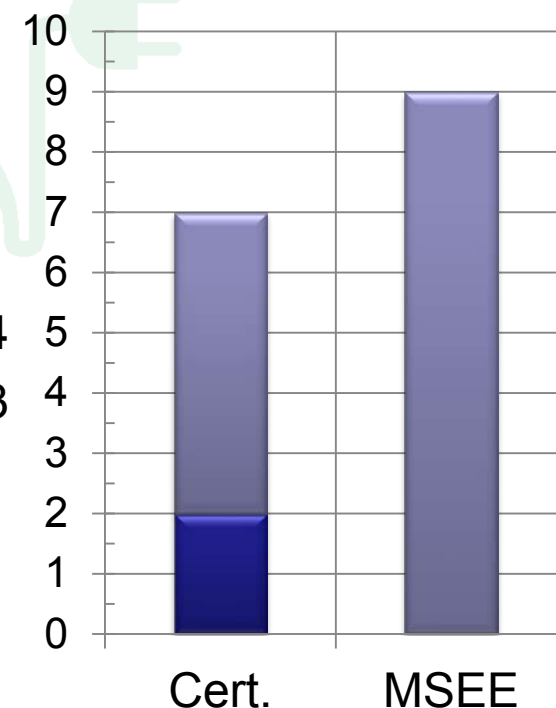
New Tech. Accomplishment: Enrollments

- 118 unique students have taken at least one IDEATE course
- 7 certificate graduates; 9 MSEE grads

Number of students having taken at least “N” courses by end of indicated fiscal year



Number of students having completed program by end of indicated fiscal year



New Tech. Accomplishment: USU / Ad

- Center co-Director Regan Zane has accepted prestigious “USTAR Professor” appointment at Utah State University
- We have reorganized center structure and leveraged this new opportunity to expand graduate certificate program
- Student still takes battery courses from UCCS; but power-electronics/drive courses from *either* CU-Boulder or USU



The University of Colorado, together with Utah State University, offer Graduate Courses and Programs in

Electric Drivetrain Technology for HEV, PHEV, E-REV, and EV

- Course offerings in battery modeling, battery management and control, power electronics for electric-drive vehicles, and motor drives leading to a **Graduate Certificate in Electric Drivetrain Technology**
- Further course offerings leading to **Masters of Science in Electrical Engineering** option in **Battery Controls** or emphasis in **Vehicle Power Electronics**
- Department-of-Energy sponsored **GATE Fellowships** available to qualified applicants

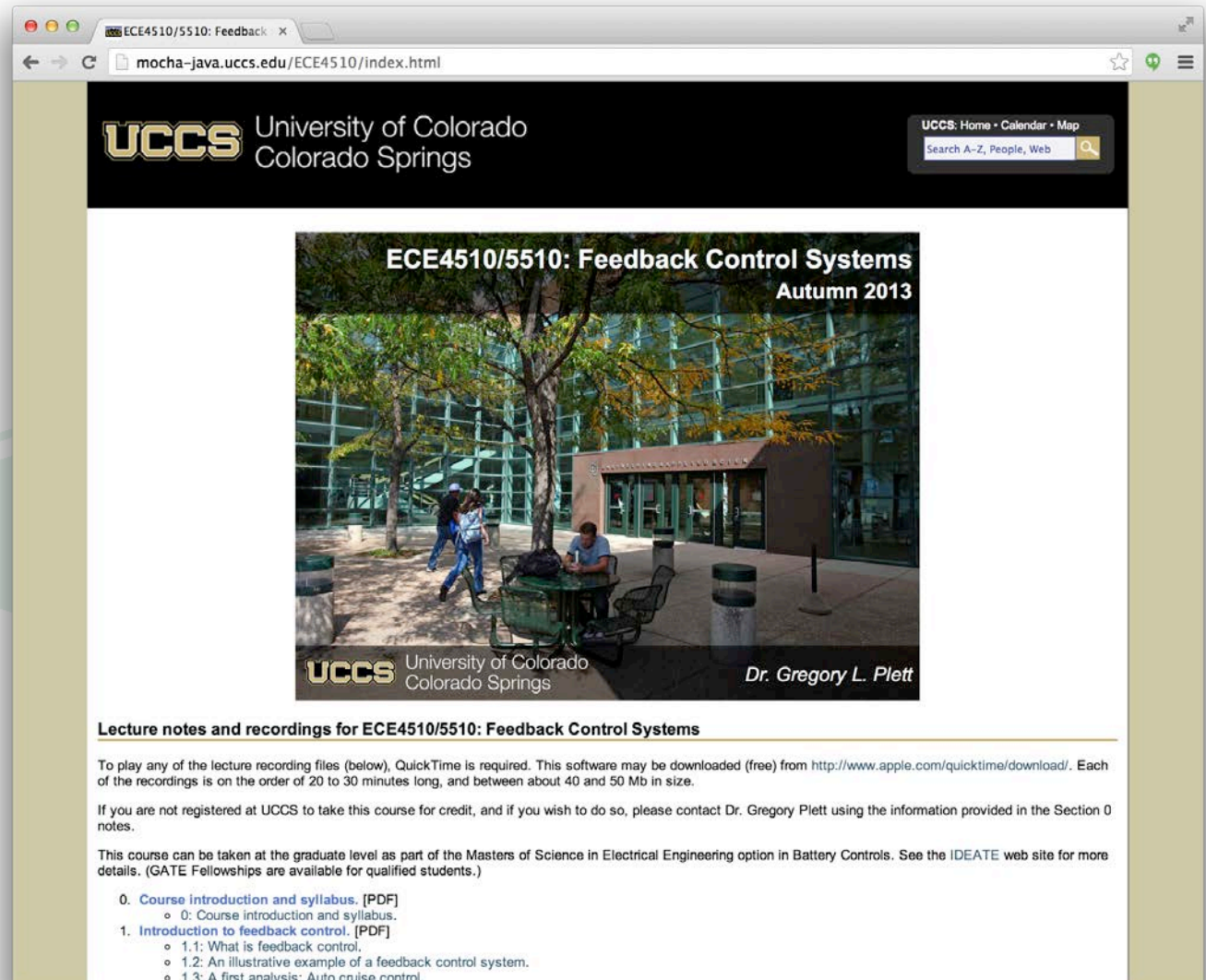
Graduate Education in Battery Controls UCCS University of Colorado Colorado Springs		Graduate Education in Vehicle Power Electronics University of Colorado Boulder / Utah State University	
Graduate courses supporting PhD in EE emphasis area in Battery Controls <ul style="list-style-type: none"> Feedback Control Digital Control Multivariable Ctrl. Systems I, II, III 	MSEE option in Battery Controls <ul style="list-style-type: none"> Optimization System Identification Kalman Filtering Model Pred. Ctrl. 	Graduate Certificate in Electric Drivetrain Technology <ul style="list-style-type: none"> Modeling Battery Dynamics Battery Management & Ctrl. Power Electronics for Electric Drive Vehicles Adjustable Speed AC Drives 	MSEE emphasis area in Vehicle Power Electronics <ul style="list-style-type: none"> Intro. to Pwr. Elect. Res., Soft Switch Model/ctrl Pwr. Elect. Pwr. Elect Lab
		Graduate courses supporting PhD in EE emphasis area Vehicle Pwr. Elect. <ul style="list-style-type: none"> Analog IC Design Mix. Signal IC Des. Renewable Energy Ctrl. Sys. Analysis Embed. Sys. Des. Digital Control Sys. 	

For more information and to apply, visit <http://mocha-java.uccs.edu/IDEATE/>

- We have developed a revised ad and have placed it in:
 - ◆ IEEE PELS Magazine
 - ◆ IEEE Electrification Magazine
 - ◆ SAE Vehicle Electrification Magazine
 - ◆ SAE Automotive Engineering (digital) Magazine
 - ◆ SAE Momentum

New Tech. Accomplishment: Packaging

- Have begun packaging MSEE-BC courses for polished on-line delivery
- Have completed packaging for *ECE5510: Feedback Control Systems*
- Have started packaging for *ECE5520 and ECE5530: Multivariable Controls I & II*



The screenshot shows a web browser window displaying the course page for ECE4510/5510: Feedback Control Systems. The page features the UCCS logo and the University of Colorado Colorado Springs name at the top. A search bar is visible in the top right corner. The main content area includes a large image of a modern building with a glass facade and a person sitting at a table in the foreground. Below the image, the course title "ECE4510/5510: Feedback Control Systems" and the semester "Autumn 2013" are displayed. The instructor's name, "Dr. Gregory L. Plett", is also shown. The page lists lecture notes and recordings for the course, including a course introduction and syllabus, and an introduction to feedback control. The page also mentions that the course can be taken at the graduate level as part of the Masters of Science in Electrical Engineering option in Battery Controls.

ECE4510/5510: Feedback Control Systems
Autumn 2013

UCCS University of Colorado
Colorado Springs

Dr. Gregory L. Plett

Lecture notes and recordings for ECE4510/5510: Feedback Control Systems

To play any of the lecture recording files (below), QuickTime is required. This software may be downloaded (free) from <http://www.apple.com/quicktime/download/>. Each of the recordings is on the order of 20 to 30 minutes long, and between about 40 and 50 Mb in size.

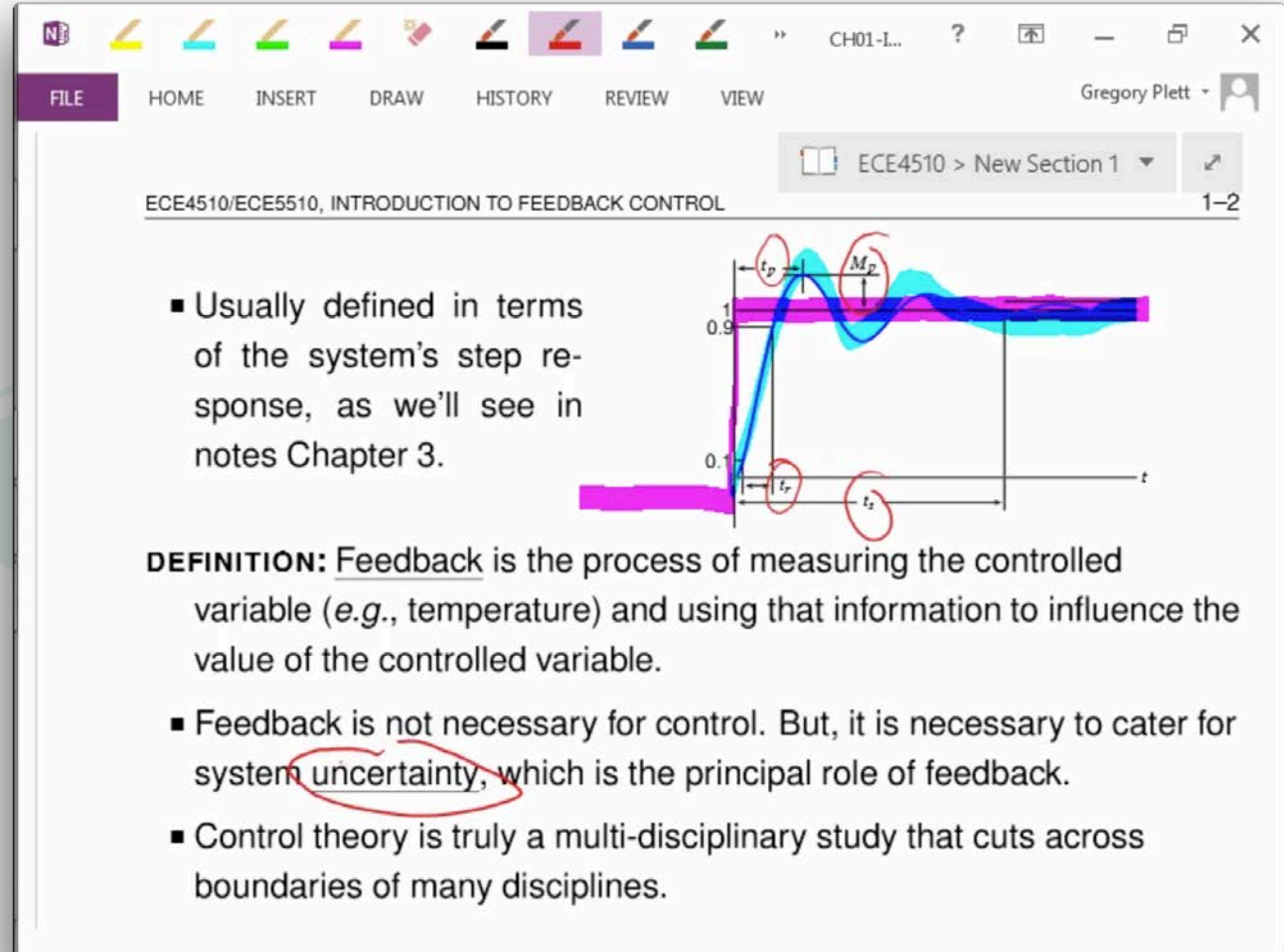
If you are not registered at UCCS to take this course for credit, and if you wish to do so, please contact Dr. Gregory Plett using the information provided in the Section 0 notes.

This course can be taken at the graduate level as part of the Masters of Science in Electrical Engineering option in Battery Controls. See the IDEATE web site for more details. (GATE Fellowships are available for qualified students.)

- 0. **Course introduction and syllabus.** [PDF]
 - 0: Course introduction and syllabus.
- 1. **Introduction to feedback control.** [PDF]
 - 1.1: What is feedback control.
 - 1.2: An illustrative example of a feedback control system.
 - 1.3: A first analysis: Auto cruise control.

New Tech. Accomplishment: Packaging

- Example screen-capture of video from ECE4510/5510 shown
- Fully typeset lecture notes, which are narrated and marked up during the lecture segment
- 72 segments, each about 20–30 min long, comprise course lecture content

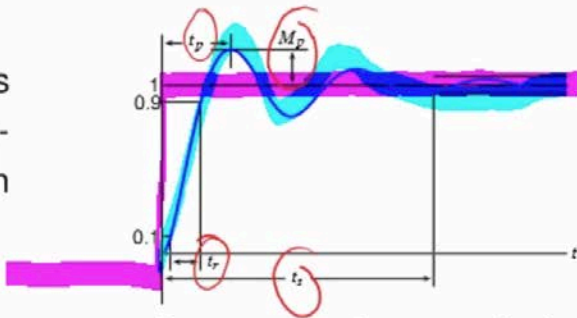


FILE HOME INSERT DRAW HISTORY REVIEW VIEW Gregory Plett

ECE4510 > New Section 1 1-2

ECE4510/ECE5510, INTRODUCTION TO FEEDBACK CONTROL

- Usually defined in terms of the system's step response, as we'll see in notes Chapter 3.

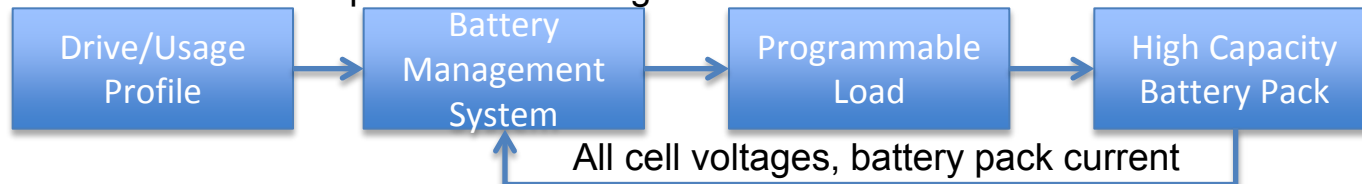


DEFINITION: Feedback is the process of measuring the controlled variable (e.g., temperature) and using that information to influence the value of the controlled variable.

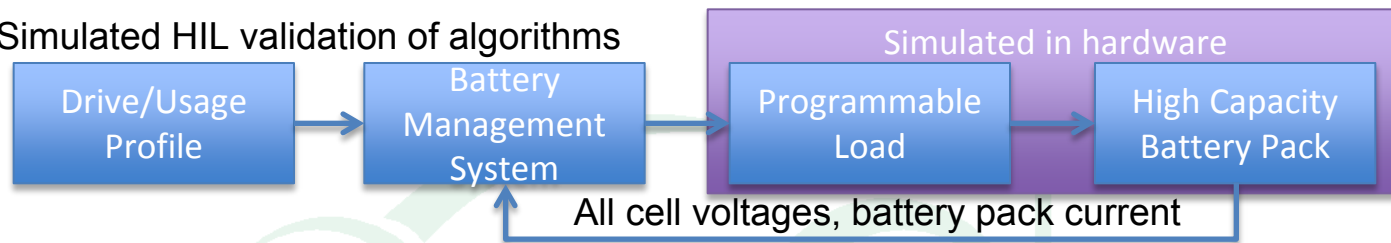
- Feedback is not necessary for control. But, it is necessary to cater for system uncertainty, which is the principal role of feedback.
- Control theory is truly a multi-disciplinary study that cuts across boundaries of many disciplines.

New Tech. Accomplishment: Simulated HIL

Real “hardware in loop” validation of algorithms



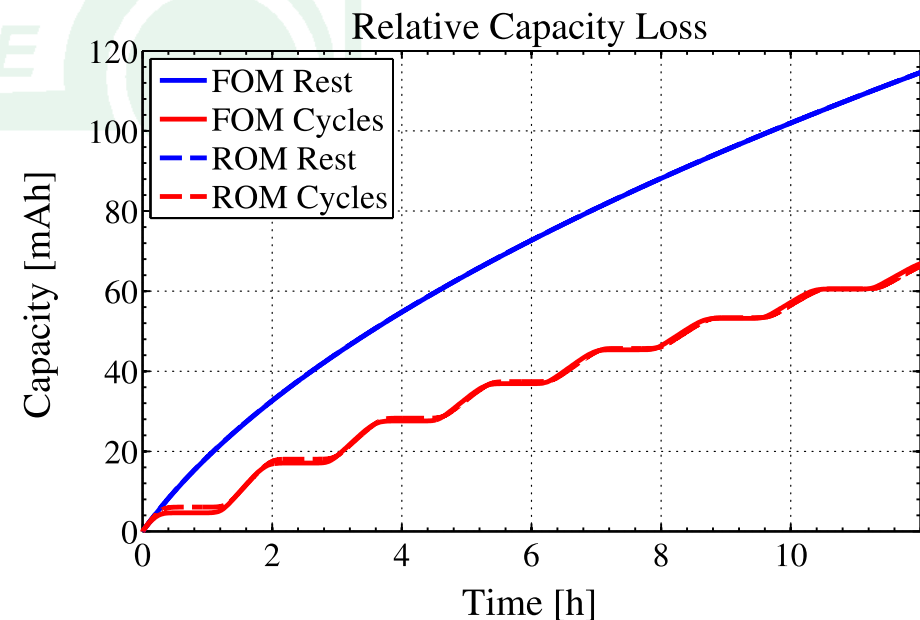
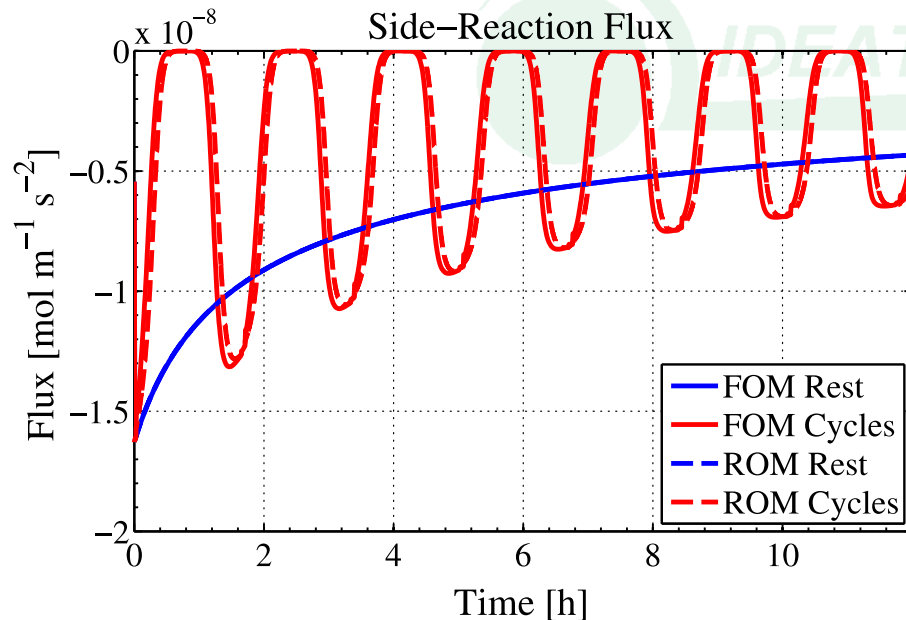
Simulated HIL validation of algorithms



- Designed and implemented hardware to simulate battery packs
- To be used for data collection, validation of battery-management-system algorithms
- Software development is ongoing

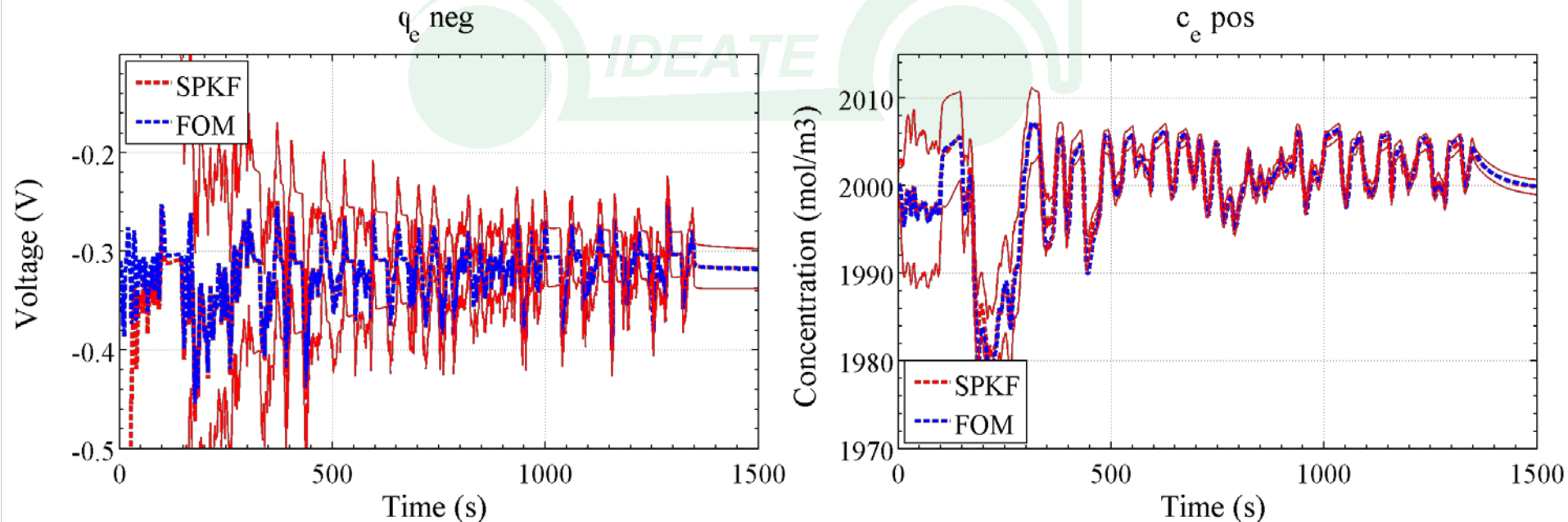
New Accomplishment: MSEE-BC Thesis

- Three MSEE-BC students completed a thesis in FY14
- *Reduced-Order Degradation Models for Lithium-Ion Cells*, L. Aldrich, Spring 2014
 - ◆ Motivation: If we can predict how a battery cell will degrade when used a certain way, we have a chance to control aging
 - ◆ Thesis: Developing controls-oriented reduced-order degradation models of the dominant known mechanisms of aging



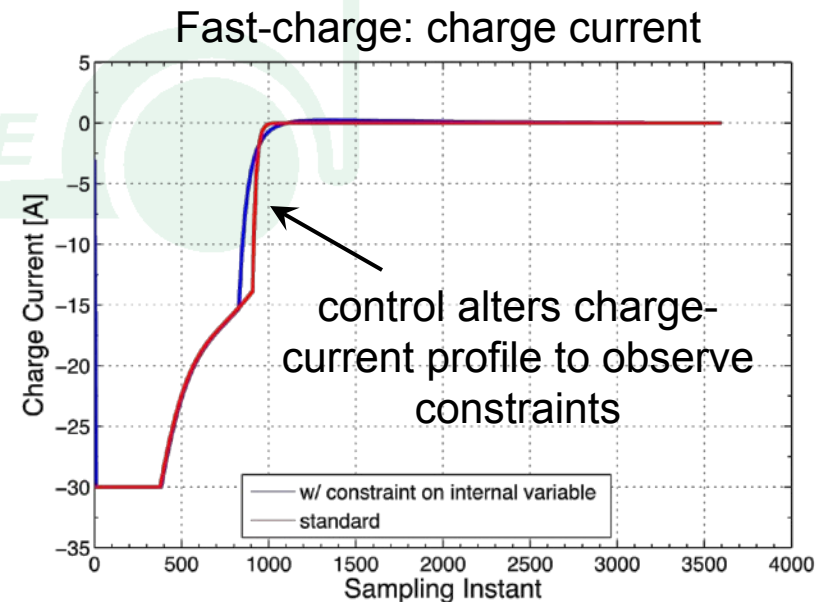
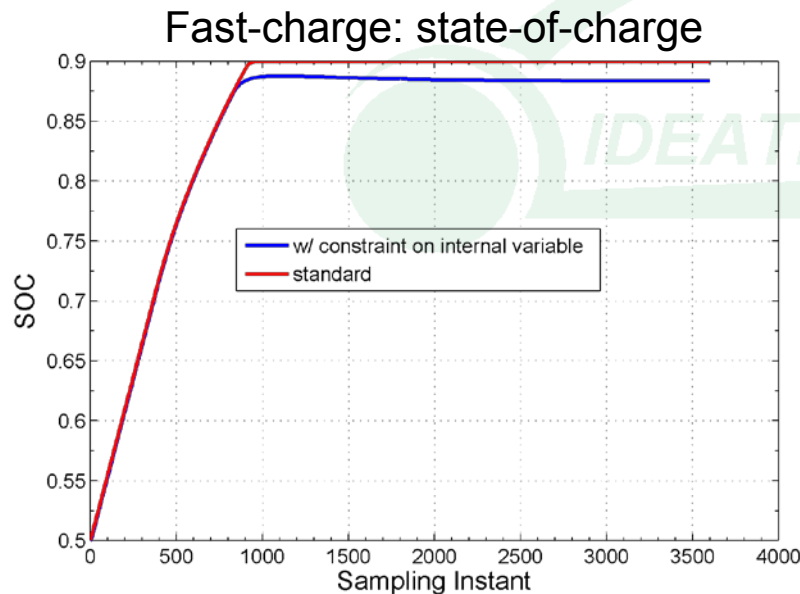
New Accomplishment: MSEE-BC Thesis

- *Model-Based Estimation of Battery Cell Internal Physical State*, K. Stetzel, Spring 2014
 - ◆ Motivation: Degradation depends on internal cell state, not (only) cell voltage. To implement controls to slow aging, must know state
 - ◆ Thesis: Using a reduced-order physics-based cell model and measurements of cell current and voltage, estimates the internal electrochemical state of a battery cell



New Accomplishment: MSEE-BC Thesis

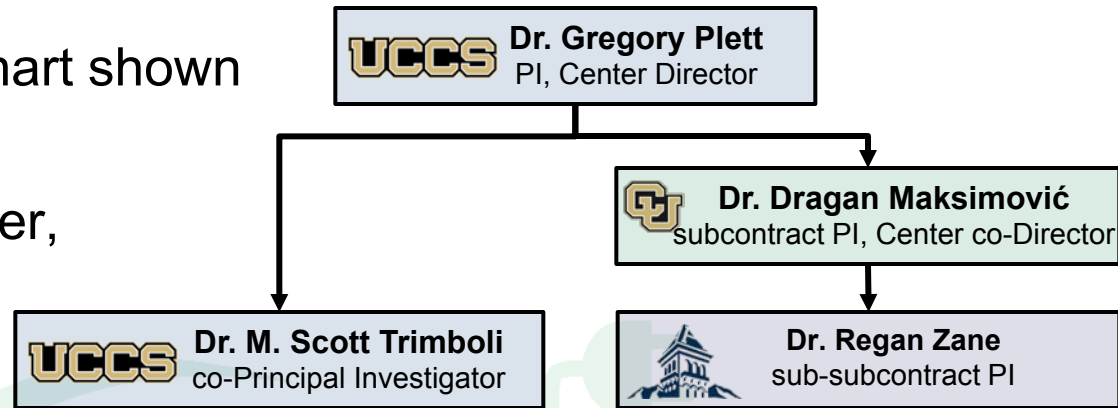
- *Constrained Model Predictive Control Applied to a Reduced-Order Physics Based Model of a Lithium-Ion Battery Cell*, K. Karami, Fall 2013.
 - ◆ Motivation: Electrochemical modeling enables access to internal state variables, making possible near-real-time control
 - ◆ Thesis: Applied charge current is modulated in such a way as to achieve desired performance objectives (e.g., extend life)



- Note: Majority of MSEE-VPE students do not complete thesis (none so far)

***IDEATE* Collaborations and Coordination**

- Team collaboration: org-chart shown
- Industry advisory board:¹



- ◆ Equipment manufacturer, vehicle companies, national laboratory, venture capital company, battery cell design/manufacturer, battery pack design companies, automotive semiconductor companies,
- This industry advisory board has expressed interest in:
 - ◆ Providing paid internship opportunities to *IDEATE* students
 - ◆ Hiring graduates from the program,
 - ◆ Providing guest lecturers as well as PhD qualified personnel to sit on thesis and dissertation committees.

¹ Arbin Instruments, Chrysler, Ford Motor Company, General Motors, Infield Capital, LG Chem Power Inc., Linear Technology, NREL, Nilar, Siemens, Tesla Motors, Texas Instruments

***IDEATE* AFM Expansion Potential**

Plans for remainder of FY14

- Refresh course curricula and content/teaching materials based on self assessment and input from Industry Advisory Board
- Continue to polish and package courses for enhanced on-line delivery, including related courses in controls and power-electronics curriculum (see next slide for schedule of packaging MSEE-BC courses)

Plans for FY15

- Offer courses to next cohort of students: first year of expansion to include Utah State University students in certificate
- Complete development of hardware battery simulator for use with algorithm verification
- Refine advertising strategy based on results of present efforts
- Continue to polish and package courses; advise MSEE students

IDEATE AFM Expansion Potential

- Continue to package all MSEE-BC courses at UCCS for on-line delivery capability to expand program reach
- Schedule determined by timetable of normal university course offerings
- Completion expected by Summer of 2016

Core (required) courses for M.S.E.E. option in Battery Controls

Elective courses for M.S.E.E. option in Battery Controls

ECE 5710
Mdl., Sim., Ident.
Battery Dynamics
(SPRING 2015)

ECE 5720
Battery Mgmt.
and Control
(SUMMER 2015)

ECE 5550
Applied Kalman
Filtering
(SPRING 2015)

ECE 5560
System
Identification
(SUMMER 2015)

ECE 5570
Methods of
Optimization
(SUMMER 2015)

ECE 5590
Model Predictive
Control
(SPRING 2016)

ECE 5510
Feedback Control
Systems
(COMPLETE)

ECE 5520
Multivariable
Control Systems I
(SUMMER 2014)

ECE 5530
Multivariable Ctrl.
Systems II
(SUMMER 2014)

ECE 5540
Digital Control
Systems
(SUMMER 2016)

ECE 5580
Multivariable Ctrl.
Systems III
(SUMMER 2016)

Summary

- *IDEATE* addresses a technology workforce shortfall with programs emphasizing two key technologies necessary to propel U.S. automotive industry to the next level, the electrified drivetrain:
 - ◆ Battery Modeling and Controls
 - ◆ Vehicle Power Electronics
- New Graduate Certificate in *Electric Drivetrain Technology* and new MSEE options will retrain traditional automotive engineers and educate new entrants to the workforce
- All administrative procedures are defined; curriculum is designed; course materials have been developed
- Have added Utah State University to certificate program
- Ongoing work in polishing courses; packaging for on-line delivery